SNE Conceptual Reference Model

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ABSTRACT: *In order to productively address a variety of issues related to representations of the Synthetic Natural Environment (SNE) and its interactions with models of military systems in M&S applications, it is advantageous to use common description languages. In addition to the need for standard data dictionaries, and data models, there is also a need for a standard system (or process) model for use as a reference against which to compare alternative system descriptions, components, decompositions, and data flows. Such a conceptual model was developed in mid-CY96 in support of a DMSO Technical Exchange Meeting on Multi-Resolution Modeling. The model has subsequently evolved to meet a variety of descriptive and analytic needs in both M&S and C^4ISR. We present an update to that model, explore its structure using functional and interface examples, describe how several contemporary M&S applications map to that model, and postulate how continued use of that model could help a sometimes fractious SNE M&S community better focus their efforts towards achieving effective data and software reuse, application interoperability, and future system development.*

1. Introduction

While the Department of Defense (DoD) Modeling and Simulation (M&S) community has a long and varied history of developing applications to meet diverse needs across the functional spectrum, it is only within the past decade that large-scale distributed simulation has become a reality.

While the High Level Architecture (HLA) defines a strong framework for establishing data (or *syntactic*) interoperability between distributed, heterogeneous applications, it is relatively weak on how individual applications should leverage that framework to achieve *semantic* interoperability. It provides basic tools for defining the public application data interfaces (termed Simulation Object Models – SOMs), and supports a negotiation process for mutually agreeing on a Federation Object Model (FOM) defining the public data to be exchanged between federated applications. It then provides a well-specified interface to a common transport mechanism for exchanging the defined data via the Run Time Infrastructure (RTI). From the perspective of modelers of military systems, this is deemed both necessary and sufficient to establish interoperability.

It is understood that a simulation consisting solely of models of military systems has limited value without incorporating a model of the physical environment (herein referred to as the Synthetic Natural Environment – SNE) within which those models of military systems will "operate". Minimally, this consists of a spatial framework relative to which military system models are positioned, and are moved. In the Real-time Platform Reference (RPR) FOM, this is the Geocentric Coordinate System; in many applications, this is some variant of an extended coordinate system based on the Transverse Mercator projection. Given well-defined instantaneous locations within this spatial framework, military system models can interact based on range and bearing. This is, of course, an impoverished view of the SNE, and most military M&S applications augment it with at least a stylized representation of the dry surface of the earth – referred to as the terrain. We define the SNE herein as follows:

SNE – The representation of the physical world within which all models of military systems exist and interact. It includes both data and models representing the elements of the environment and their effects on military systems, and models of the impact of military systems on environmental variables (e.g. contrails, dust clouds from moving vehicles, spoil from combat engineering).

Over the past five years, increasing attention has been paid to the complexity and importance of the physical environment as a critical mediator of *all* military interactions, and therefore an important element in any effective DoD M&S application. The Defense Modeling and Simulation Office (DMSO) M&S Master Plan (MSMP) [1] identifies three "Natural Environment" Executive

Agents as responsible for "authoritative representation" in the inter-related domains of terrain, ocean, and air & space.

These organizations have generally focused their efforts on understanding environmental data requirements and associated data production issues, and are only relatively recently beginning to venture into issues related to data distribution and run-time environmental modeling. Discussions at the former Distributed Interactive Simulation (DIS) workshops, as well as at SIW, have often tackled these run-time related issues under the guise of "the environmental architecture", suggesting either that environmental modeling has demands incommensurate to those for military system modeling (i.e., "a building *is not* like a tank"), or (at the other extreme) that a literal reuse of existing approaches to distributed military system modeling can be applied to distributed environmental modeling (i.e., "a cloud *is* just like a tank").

Meanwhile, the Synthetic Environment Data representation and Interchange Specification (SEDRIS) project continues to tackle the need for standard data models, and data dictionaries, for SNE. While their focus has been explicitly limited to pre-execution data definition and distribution, it is widely expected that the common environmental descriptive mechanisms being developed through broad SNE community participation in SEDRIS will form a major foundation for run-time environmental modeling.

Missing amongst all of these activities (and especially obvious given the current state of the "environmental architecture" controversy), is a standard system (or process) model for use as a reference against which to compare alternative environmental run-time system descriptions, components, decompositions, and data flows.

It is critical to understand that we do not propose a specific "environmental architecture", either from the perspective of the federation, or the federate, designer. We instead propose a *conceptual reference model* framework within which alternative environmental architectures and designs (whether distributed or stand-alone), can be dissected, described, compared and contrasted, and ultimately used to achieve the complex goal of interoperability among distributed heterogeneous applications. We firmly believe that "one [design] *does not* fit all"; we advocate, however, the view that "one [conceptual framework] can fit all", and propose herein to justify that view.

In this paper, we:

1. Present the SNE conceptual reference model,
2. Explore its structure using functional and interface examples,
3. Describe how several contemporary M&S problems map to that model, and
4. Postulate how use of this model could help the SNE M&S community better focus their efforts towards achieving effective data and software reuse, application interoperability, and future system development.

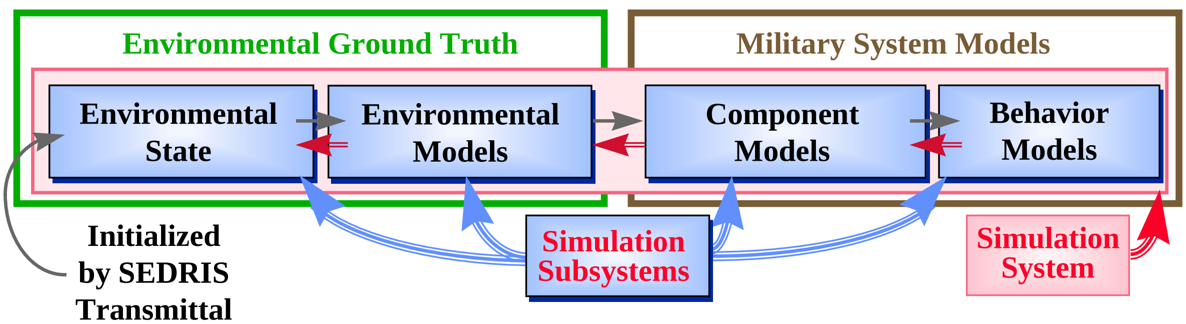


Figure 1: Conceptual Reference Model Schema

2. Conceptual Model Structure

2.1 Schematic Model

The SNE Conceptual Reference Model was developed from the perspective of a federate designer. As illustrated in Figure 1, at its most simplistic it can be viewed as two major components contributing to a single simulation system (or application): the [SNE] Environmental Ground Truth, and the Military System Models. The former furnishes the simulated environmental context within which the (latter) military system models operate.

An interesting question arises in regard to the physical manifestations of military systems. Is the vehicle (e.g., or weapon, or sensor) structure part of the Environmental Ground Truth? Yes. For the same modeling reasons that a building is – it provides the measurable attributes/values used to describe the physical environment. In particular, the vehicle surface responds to illumination (radiant energy; whether solar or target illuminator) as does any other surface in the SNE, and interacts with other surfaces according to the same (typically) Newtonian laws of motion and collision. It is a physical, space-occupying mass.

Remember that this is a *conceptual model*, so no claim is being made that specific simulations will (or should) chose to implement this particular decomposition. What is important is that *conceptually*, we should model the physical manifestations of military systems in exactly the same way as we model the physical manifestations of the environment. To the extent we chose not to, we have introduced inhomogeneity in the fidelity of the representation of the physical environment. This may be desirable from a systems engineering perspective, however we must recognize when we make (and the implications of making) this choice.

Each of these two major simulation system components, Environmental Ground Truth and Military System Models, is further subdivided into a total of four subsystem types with associated interconnections (generic data flows). These four subsystem types are:

Environmental State – The collection of data defining the measurable attributes/values used to describe the SNE at a point in time. Specific values may, however, represent time-varying conditions (e.g., Sea State as a synopsis of the constantly changing geometry of the ocean surface). This state would be initialized via a SEDRIS transmittal, then evolve in response to other inputs.

Environmental Models – The collection of algorithms used to derive additional SNE-related data (e.g., "emergent properties" such as geometric occlusion along a path), or evolve the state of the SNE over time in response to internal and external factors (e.g., diurnal temperature, smoke caused by burning structures, blast damage due to munitions, acoustic byproducts of movement).

Component Models – The collection of algorithms used to model military equipment ("men and material"). These are generally the space-occupying physical manifestations of the military systems, minimally including location and extent (e.g., planes, missiles, and supplies).

Behavior Models – The collection of algorithms used to model how military equipment is employed in response to existing conditions (e.g., doctrine, tactics, planning, problem solving). While the *sine qua non* of constructive simulations, virtual simulations replace these models by direct participants / trainees (e.g., fighter jet crew, command post staff, individual combatants).

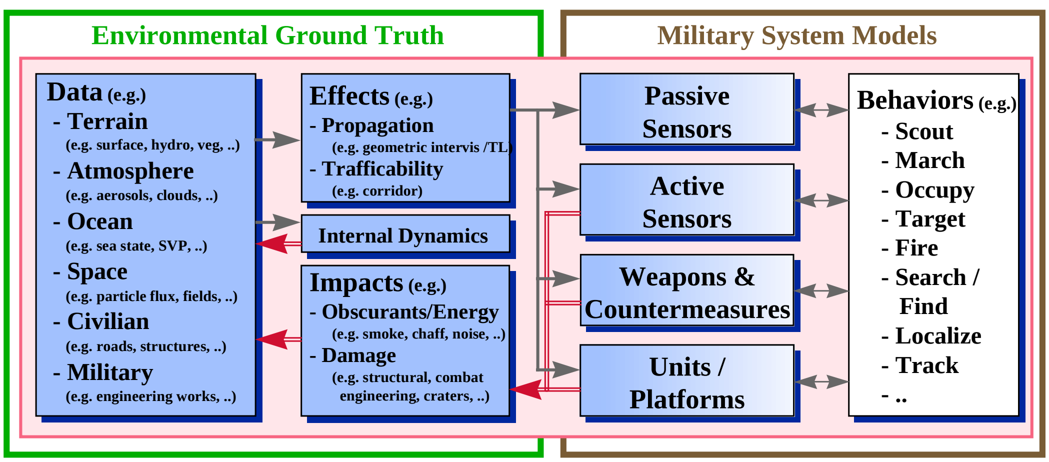


Figure 2: Conceptual Reference Model

2.2 Full Model

The schema is further refined in Figure 2, to define a fully functional *conceptual* application.

Both Environmental Models and Component Models subsystem types have been further decomposed, and major data flows among the defined subsystems have been refined. The shading across the subsystem types indicates the degree to which environmental data dominates processing activities, decreasing from left to right. The four Component Model types are self explanatory, however the three Environmental Model types are not.

Environmental Effect – A direct influence of the environment on sensors (active and passive), weapons & countermeasures, and/or units/platforms (e.g., ducting of acoustic energy by ocean's vertical density structure; impaired tank movement due to rain-soaked soil). Environmental effects models may be as simple as a "pass-through" of environmental state in the immediate vicinity of a military system model.

Environmental Impact – A direct influence on the environment caused by active sensors, weapons & countermeasures, and/or units/platforms (e.g., bomb crater on runway, cooling of atmosphere due to smoke from burning tanks, acoustic noise caused by civilian shipping).

Environmental Internal Dynamics – The algorithms modeling physical processes that cause spatial and temporal variations in environmental state variables. These processes may be represented by either distinct data sets that define the environmental state at a sequence of times or by algorithms implementing mathematical models of some form (e.g., deterministic or stochastic differential or difference equations).

As an inexact analogy, Environmental Ground Truth forms the gaming board and Military System Models comprise the gaming pieces. The rules of play are tightly coupled to the configuration of gaming pieces on the board via their locations and interactions as mediated by the environment. And (most interestingly) all the while, the gaming board is changing configuration (environmental dynamics).

3. Functional and Interface Examples

Although we have attempted to declaratively specify the individual *conceptual* subsystems in an unambiguous manner, further description and "usage" examples (or operational definitions) should help clarify how they relate to environmental modeling in instantiated M&S applications familiar to individual readers. We will proceed from left-to-right along the primary direction of environmental data flow, focusing on subsystems of Environmental Ground Truth.

Environmental Data (the only subtype of Environmental State herein defined) has been elaborated through subdivision along environmental domains, in addition specifically identifying man-made environmental features in the two categories of Civilian and Military infrastructures. These include most "non-natural" environment data, although the impacts of military systems do appear in other domains (e.g., atmospheric particulates due to burning vehicles, ocean acoustic signals induced by active sonar or engine noise). The exact division into Environmental Data domains is not intended as prescriptive, and will vary from system to system. The sum total of Environmental Data is the instantaneous state of the physical world being represented in the application.

Environmental Effects address the fact that models of military systems require information about the physical environment that is non-local in nature. The primary example of this relates to the propagation of energy in the environment and its interaction with military systems (e.g., sensors). *Conceptually*, energy in the environment should be treated the same as mass in the environment – that is, modeled at all locations (in all directions, at all frequencies, etc.) and the results represented as Environmental Data. Passive Sensor Models, e.g., need to know the energy impinging on their aperture (given a position, look-angle, field-of-view, etc.). Propagation, or transmission loss, Environmental Effects models determine the cumulative effect of the environmental state along the propagation path (e.g., a geometric intervisibility ray in the optical spectrum through a homogeneous non-refracting medium), and "deliver" that cumulative state to the aperture of the Passive Sensor Model. Similar arguments apply in the case of vehicle motion and environmental trafficability. Environmental Effects "feed" all Component Models.

Environmental Impacts, conversely, address how military systems intentionally or inadvertently change the state of the environment. To continue the Passive Sensor Model example, a surface ship underway creates energy (an acoustic signature) which is "injected" into the environment. More precisely, Environmental Data representing the location and qualities of that energy are created and managed by the "Ship Acoustic Signature" Environmental Impacts model. That data subsequently becomes available to an "Acoustic Propagation Loss" Environmental Effects model, which ultimately feeds the Passive Sensor Model. Yes, this is a slightly complicated sequence of processing stages that typically isn't implemented as such in current Naval On-Board Trainer (OBT) simulations. But *conceptually*, we propose that this sequence of processing stages takes place, *even if only in the mind of the system designer*. We leave additional examples as an exercise to the reader. All Component Models potentially have Environmental Impacts, however for purposes of clarification, we have intentionally identified Passive Sensor Models as not impacting the physical environment *per se* – the physical manifestations of these would *conceptually* be "handled" by the associated "platform" (or vehicle).

Given that one of our major challenges in the community is to establish valid interoperability between heterogeneous simulations, having a common description language to use in comparing these alternative decompositions is critical to success.

As Figure 3 illustrates, the preceding end-to-end trace of data flow from "Ship" Component Model to "Ship Acoustic Signature" Environmental Impacts model to "Acoustic Energy" Environmental Data to "Acoustic Propagation Loss" Environmental Effects model, and finally to "Passive Sensor" Component Model affords greater opportunity for comparing alternative process flows, models, and implementations than merely stating that "ship entities have acoustic signatures which are sensed by sonars". Unfortunately, the community is currently in the latter situation and progress in developing a common understanding has been limited to date.

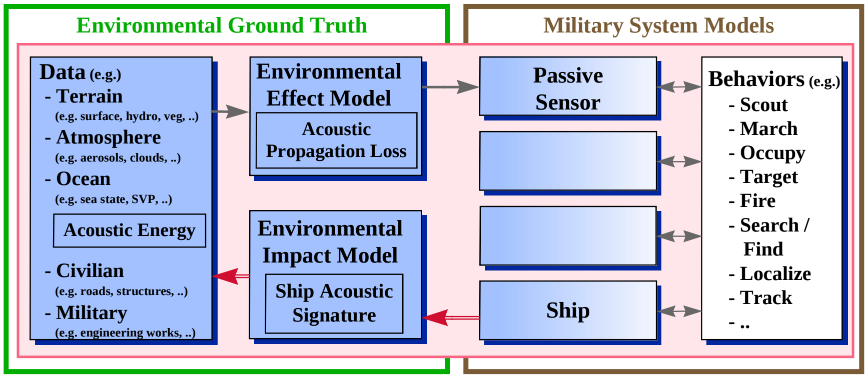


Figure 3: Acoustic Data Processing

Internal Dynamics address the evolution of the environment in time and space as determined by non-military factors. These can be as simple as an ephemeris model of solar illumination associated with a terrain surface thermal model, or as complex as a full Numerical Weather Prediction (NWP) model which must be executed in advance of the simulation.

Figure 4, for example, shows the situation in the DARPA Synthetic Theater of War (STOW) federation as regards atmospheric data [6]. As illustrated, in advance of the federation execution an off-line process of scenario development (using NWP data conceptually accessed via SEDRIS) creates a 4D (time and space) data set describing the internal dynamics of the atmosphere. During federation execution, an Internal Dynamics Environmental Model implemented as the union of the TAOS Distributor plus the prepared data set regularly updates the Environmental Data as accessed by all federate Environmental Effects Models.

Note that the Internal Dynamics Environmental Model for atmospheric data in STOW is not affected (as indicated in Figure 4) by other changes in Environmental Data (e.g., transpiration rates of local vegetation).

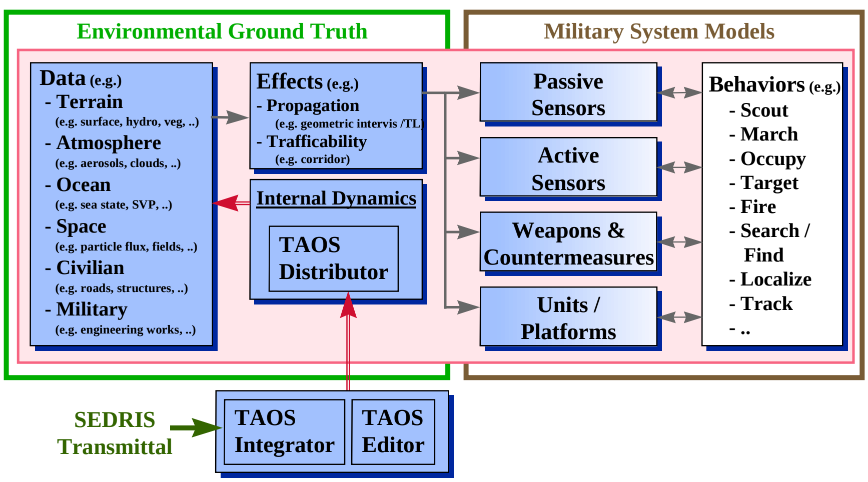


Figure 4: STOW Total Atmosphere and Ocean Services

4. Mapping to Contemporary Problems

4.1 Specifying Simulations

Designing, populating, and maintaining a SNE is a non-trivial undertaking. As an "environmental modeling" developer, it is currently impossible to find a well-specified description of a SNE from which to establish traceability of requirements or testability of results. As a result, building a SNE is essentially a "seat of the pants" undertaking fraught with much risk – both over-building and under-building are possible (and likely).

Traditionally, simulations are specified in terms of their included models of military systems and how those models will interact to achieve the intended purpose of the simulation. Occasionally, specifications will reference general SNE features such as "terrain, weather, vegetation", or identify specific data sources to be used in populating the SNE (e.g., DTED I). In almost no case do requirements developers specify how the Military Systems Models should be influenced by the Environmental Ground Truth (and specific elements thereof). The result is a great deal of leeway for SNE developers. The typical downside is that, system development resources being fixed, "when in doubt" the resources allocated to SNE development are minimized, to the long-term detriment of the resulting simulation (SNE enhancements often being difficult to retro-fit to a fundamentally flawed simulation design). The SNE Conceptual Reference Model gives us some clues as to "a better way".

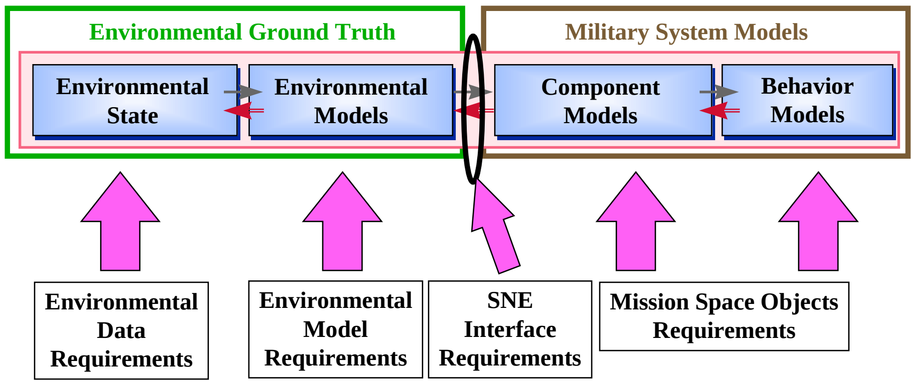


Figure 5: Requirements Implications

As illustrated in Figure 5, there are really four types of requirements which simulation developers need to explicitly specify in regard to the SNE. First (to use terminology from the Joint Simulation System – JSIMS), there are the usual requirements for Mission Space Objects (MSO – models of Military Systems). What is typically missing (or severely limited) is the specification of environmental data elements which MSOs must respond to, how they will react, and which environmental data elements they will impact. These dependencies/relationships become clear using the SNE Conceptual Reference Model.

Second, given a well-formulated definition of MSOs in terms of Component Models and their interactions with Environmental Ground Truth, it is possible to develop a clean definition of the interface requirements between Environmental Ground Truth and Military System Models (MSOs taken as a whole). This has clear implications for parallelizing system development and potential reuse.

Third, recognizing the inherent decomposition of the Environmental Ground Truth into State/Data and Models encourages good specifications of State/Data to be populated from SEDRIS transmittal(s) and subsequently maintained over the course of the simulation, separately from the Models (algorithms) to be reused (or implemented *de novo*) which will manipulate that data (effects, internal dynamics, and impacts). Not only are better specifications encouraged, and potential reuse enhanced, but to the degree that reuse occurs, cross-federation interoperability improves. And to the degree that good specifications are prepared, the development of both the simulation SOM, and subsequently the federation FOM, are simpler and more likely to be correct and complete.

The bottom line is that the SNE Conceptual Reference Model potentially provides "a better way" to think about specifying, developing, and reusing both data and system components within simulations and federations. Consistent use of the SNE Conceptual Reference Model should lead to reduced life-cycle costs and improved interoperability across the M&S community.

4.2 Federating Simulations

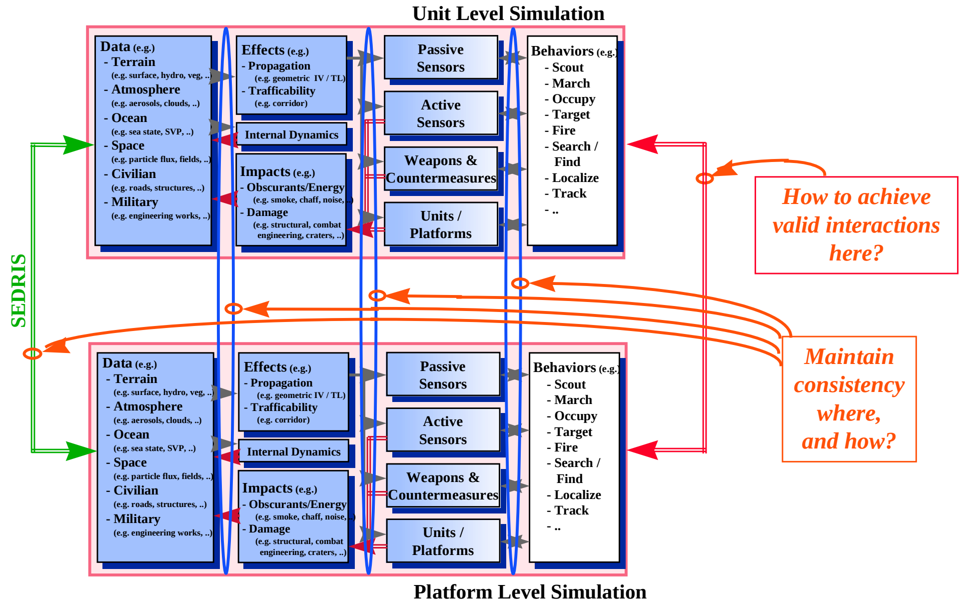
A continuing, barely addressed, challenge in the distributed environmental simulation community is the attempt to federate individual simulations not designed with federation in mind. The good news is that few existing simulations include a robust Environmental Ground Truth. The bad news is that every existing simulation has *some* Environmental Ground Truth, and as we enter FY99, *every* simulation is mandated to support the HLA. The result will be a plethora of federating simulations with little understanding of the *semantic* implications of establishing data interoperability using the RTI.

Given that interoperability is a much-abused term, we adopt instead the following definition:

Consistency – Agreement (within statistical limits) between results (final or intermediate) of different simulations of the same scenario.

In the context of federating two simulations, we propose that one goal might be to achieve valid interactions at the Behavioral Modeling level and that, more precisely, the issue is to achieve *inter-simulation consistency* as required by the usage of the federation (e.g., training).

Figure 6 illustrates a pair of hypothetical instantiations of the SNE Conceptual Reference Model: a unit-level and a platform-level constructive simulation. As good federation engineers, we initialize their Environmental Data subsystems with the same SEDRIS transmittal. We then might ask the question, "To the degree that the simulations are inconsistent (choose your own metric) where does this inconsistency arise and what is its root cause?"



igure 6: Consistency and Interoperability

Without a shared conceptual view of how these two simulations are structured, and what are their primary conceptual subsystems, we have no basis for identifying where to take measures, what might be appropriate to measure, or what the results of the measurements mean in terms of simulation operation and "upstream / downstream" data processing. Clean conceptual separation of Environmental Ground Truth from Military System Models (and subdivisions within the Environmental Ground Truth) is a powerful tool for determining where inconsistencies lie in a federation.

These "test points" are, of course, not a new concept. ZCAP©[3][5], for example, instantiates one such approach to measuring consistency among terrain and civilian Environmental Data in different simulations. It also incorporates basic methods for evaluating the terrain and civilian Environmental Data in the context of a fixed "geometric intervisibility" Environmental Model. Other tools in the community [4] delve more deeply into Environmental Data inconsistencies, initially within simulations but ultimately within SEDRIS transmittals.

More recently, the DARPA Advanced Simulation Technology Thrust (ASTT) has been engaged in extending these concepts by defining tactically meaningful "Measures of Consistency" and conducting experiments at a number of the "test points" identified in Figure 6 [2].

By adopting a common description language, alternative system descriptions, components, decompositions, and data flows become possible to unambiguously describe and discuss. It is reasonable to expect that this will ultimately result in the definition (and future development) of more consistent distributed environmental models.

4.3 Multi-Resolution Modeling

In a simulation of limited computational resources there is always a trade-off being established between military model resolution, and the number of military models which can be executed. In the constructive simulation community this trade usually evidences itself as the development of "unit level" military models in which combat outcomes are not adjudicated based on vehicle-vehicle interactions, but rather in terms of larger forces and less precise outcomes (e.g., companies lost, percent supplies destroyed).

With increasing emphasis on federating simulations for a variety of purposes, and the ongoing development of a new generation of constructive unit-level simulations (e.g., JSIMS and JWARS), these is much interest in how to ensure that virtual simulations (e.g., the Army Close Combat Tactical Trainer – CCTT, the Navy Battle force Tactical Trainer – BFTT, or the Air Force Distributed Mission Trainer – DMT) validly interact with constructive simulations such as JSIMS.

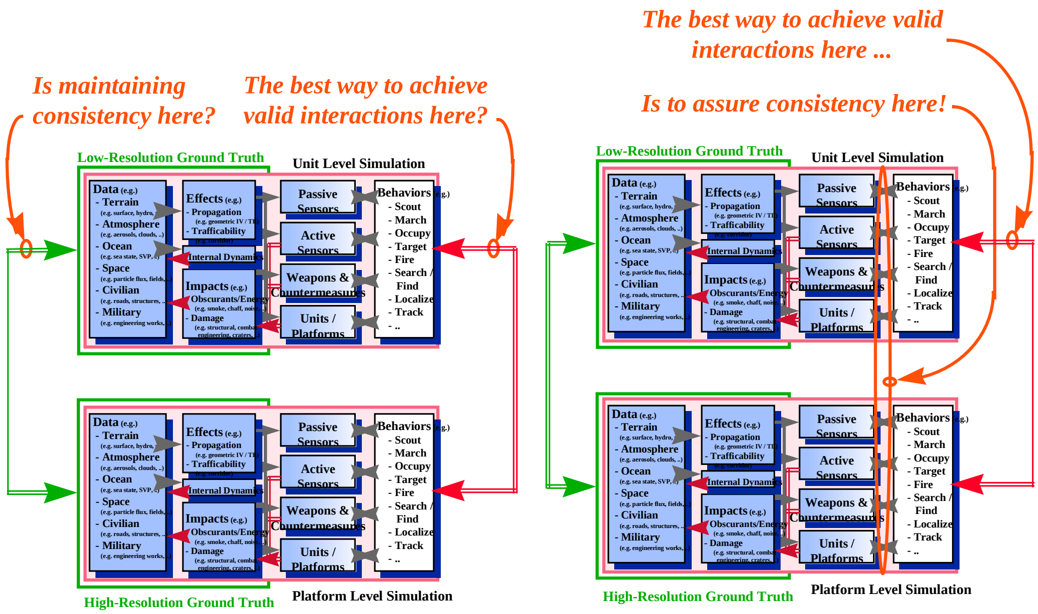


Figure 7: Multi-Resolution Interoperability

As illustrated in Figure 7, federating unit- and platform-level constructive simulations offers interesting challenges as regards defining valid interactions and how they might best be achieved. Casting the problem in terms of the SNE Conceptual Reference Model leads one to the conclusion that consistency at the output of the Component Models (basically "environmental perceptual consistency" as regards the Behavior Models) is much more likely to result in valid simulation interactions than consistency at the Environmental Data outputs. Furthermore, a rational federation design for explicitly achieving multi-resolution modeling consistency might look as illustrated in Figure 8.

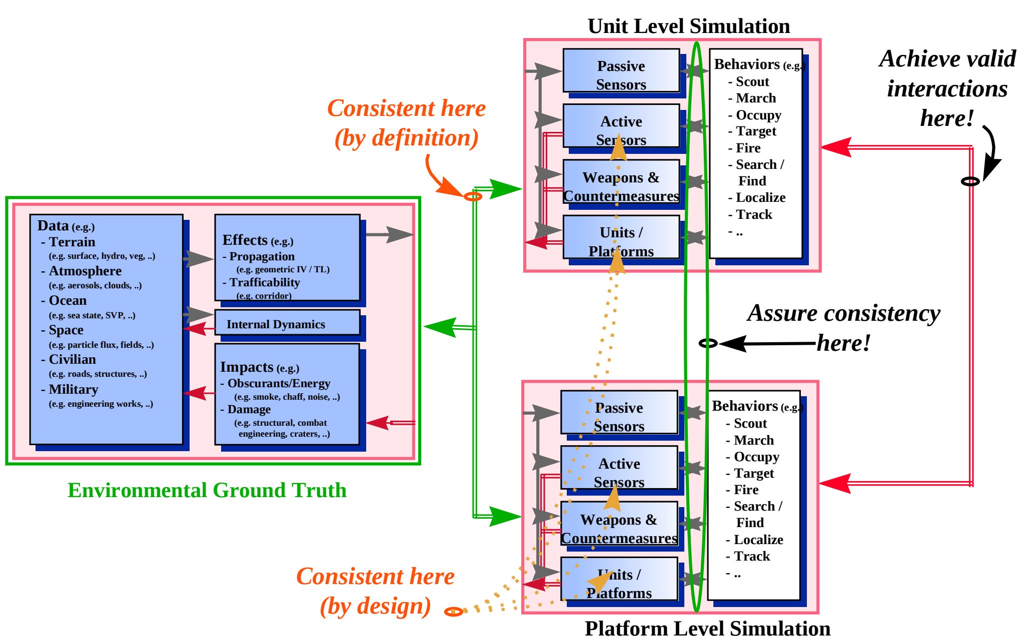


Figure 8: Multi-Resolution Military Models

This diagram suggests that explicit sharing of a single Environmental Ground Truth across both applications, coupled with development of explicitly consistent multi-resolution Component Models, may in some cases be preferable to developing and maintaining (in the face of environmental dynamics) consistent multi-resolution Environmental Ground Truth subsystems. DARPA ASTT is currently investigating issues raised by this conjecture.

Whether the conjecture ultimately proves true or false is not critical to the realization that the SNE Conceptual Reference Model lets us quickly diagram and (we hope unambiguously) discuss this type of "architectural" issue. "Diagram and discuss" is difficult to do in the environmental modeling community today due to the lack of a well-understood system description "language".

4.4 Command and Control

M&S is not the only class of applications which can potentially benefit from the SNE Conceptual Reference Model. Command and Control applications (more generally – C^{4}ISR) also incorporate environmental models for a variety of purposes. Certainly it is the case that all planning is essentially simulation.

Component Models would be better termed "Equipment Models", although there is no fundamental difference between them. On the other hand, Behavior Models would be replaced by "Battle Command Decision Support" which while incorporating many aspects of M&S Behavior Models from the constructive community, is fundamentally aligned towards *supporting* warfighter decision making, rather than *modeling* it.

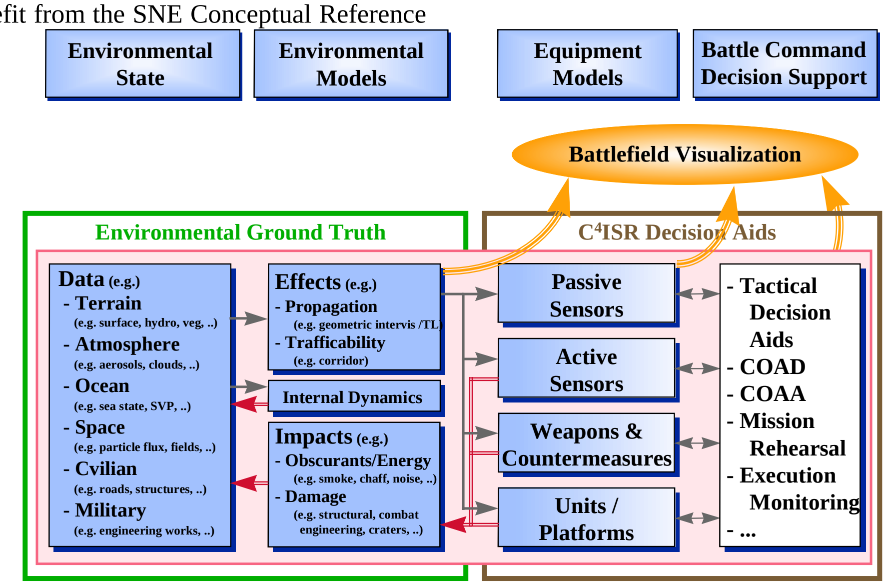


Figure 9: Example C4ISR Application

Figure 9 illustrates how the Military System Models component of the basic SNE Conceptual Reference Model would be modified to accommodate the new C^{4}ISR Decision Aids component (and the renaming of associated subsystems and example decision support functions). In current C^{4}ISR systems, Environmental Ground Truth is essentially static (so the Internal Dynamics Environmental Models subsystem should be deleted) and the remaining Environmental Models are fairly primitive in nature.

Also illustrated is the relationship of the SNE Conceptual Reference Model to the current emphasis in the DoD (and especially the Army) on "Battlefield Visualization". From one perspective, Battlefield Visualization, at least as currently practiced, is about Human-Computer Interaction (HCI) and the presentation of military information in a form most readily assimilable by warfighters. As such, it is mainly about displaying military information embedded within 4D views of the battlespace from the perspective of a warfighter (albeit one who can virtually assume any physical location desired).

Placed in terms of the SNE Conceptual Reference Model, Battlefield Visualization requires information from Environmental Effects (omniscient view), Passive Sensors (limited view), and decision aids generating the contextually appropriate significant military data. What is important to realize is that, much like the previous discussion on specifying simulation requirements, there is a marked lack of understanding in the C^{4}ISR community about the dependencies of effective Battlefield Visualization on Environmental Ground Truth, and thus an inability to effectively specify their SNE requirements.

These issues are particularly relevant to training simulations like JSIMS which are effectively "virtual simulations" where the attached C^{4}ISR system is the "crew station" for the warfighter trainee. It is highly likely that the Environmental Ground Truth as perceived by a JSIMS trainee using a C^{4}ISR situation monitor will be inconsistent with that perceived by a JSIMS MSO; another interesting interoperability problem which emerges as M&S becomes inextricability intertwined with C^{4}ISR systems (whether called "embedded training" or "Course of Action Analysis").

Again, the SNE Conceptual Reference Model helps us clarify the major system components and dependencies, thus encouraging fruitful systems engineering discussions, requirements specification, systems design, reuse, and resulting interoperability.

4.5 Non-DoD Applications

Any computer application that references SNE data – not just the DoD-specific situations described thus far – can benefit from analysis in terms of the SNE Conceptual Reference Model. For example, GIS technology is often used to plan new housing areas where many SNE-relevant factors (transportation, drainage patterns, existing infrastructure, etc.) need to be considered. The SNE Conceptual Reference Model provides a basis for decomposing and organizing these factors, and relevant analyses, into a coherent view of their relationships and dependencies as a first step towards designing a complete model of the proposed development, its impact on surrounding areas, and the effect of environmental conditions on its "liveability" for potential occupants.

5. Conclusions and Next Steps

The SNE Conceptual Reference Model appears to have the basic power to help the SNE community focus their efforts in the areas of environmental modeling system description and design. In particular, it appears to offer the opportunity for the community to leverage their experiences in a form which could be at least descriptive of existing environment modeling systems, and perhaps serve as a basis for a prescriptive approach to next-generation development activities. The M&S "Natural Environment" Executive Agents might find it useful in future "architecture related" efforts. Systems already in development might benefit from the induced rigor in specifying SNE-related requirements and establishing a basis for discussions (and plans) for future interoperability.

Like SEDRIS, the SNE Conceptual Reference Model is a work still in-progress; one based on encouraging and supporting focused, productive community development. It is still immature, based as it is on only a few experienced perspectives. Worse still, it is not a supported effort in the community and stands roughly where SEDRIS stood 2 years ago – waiting for a concerted effort to see where it could go, through judicious elaboration based on existing systems, testing against new concepts, and application to problems of immediate relevance.

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Author Biography

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